

Evidence for $\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-$

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Abstract

Using 121.4 fb^{-1} of data collected with the Belle detector at the $\Upsilon(5S)$ resonance at the KEKB asymmetric-energy e^+e^- collider, we report evidence for the $\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-$ decay mode with a measured branching fraction $(3.6 \pm 1.1[\text{stat.}]^{+0.3}_{-0.5}[\text{syst.}] \pm 0.9[\Lambda_c^+] \pm 0.7[N_{\overline{B}_s^0}]) \times 10^{-4}$ and a significance of 4.4 standard deviations. This is the first evidence for a baryonic B_s^0 decay.

1. Introduction

Results on baryonic B -meson decays obtained by Belle [1–6] and BaBar [7–12] have increased experimental and theoretical interest in such processes [13]. B -meson decay modes with two- [1, 2, 7, 8], three- [2–5, 8–11] and even four- [2, 6, 10–12] and five-body [11] final states have been observed. The measured branching fractions clearly follow a hierarchy that depends on the final-state multiplicity: two-body channels have smaller branching fractions compared to multi-body ones. In addition, most three-body baryonic B -meson decays have a near-threshold peak in the invariant baryon-antibaryon mass spectrum. This effect was investigated in Ref. [14]. In this paper, we report the first evidence for the $\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-$ decay and compare the measured branching fraction with that for a similar channel, $B^- \rightarrow \Lambda_c^+ \overline{p} \pi^-$ [4], where the s -quark of the decay under study here is replaced by a u -quark [15].

2. Data Sample and the Belle Detector

The data for this analysis were taken with the Belle detector at the e^+e^- asymmetric-energy collider KEKB [16] at the $\Upsilon(5S)$ resonance. The integrated luminosity of the sample is 121.4 fb^{-1} and corresponds to $(7.1 \pm 1.3) \times 10^6$ $B_s^0 \overline{B}_s^0$ meson pairs [17] produced in three $\Upsilon(5S)$ decay channels: $B_s^{*0} \overline{B}_s^{*0}$, $B_s^{*0} \overline{B}_s^0$ and $B_s^0 \overline{B}_s^0$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect K_L^0 mesons and identify muons (KLM). The detector is described in detail elsewhere [18].

3. Selection Criteria

We use selection requirements that were previously used for baryonic B -meson decay analyses [5]. Charged tracks, except those from K_S^0 and Λ , are required to originate within 0.25 cm in the radial direction and within 1 cm along the beam direction from the interaction point (IP). We distinguish a charged particle of type A from one of type B (A and B being π , K or p) based on likelihood values $\mathcal{L}(A)$ and $\mathcal{L}(B)$ derived from the TOF, ACC, and dE/dx measurements in the CDC.

K_S^0 mesons (Λ hyperons) are reconstructed in the $K_S^0 \rightarrow \pi^+\pi^-$ ($\Lambda \rightarrow p\pi^-$) decay mode by fitting the pion (p and π) tracks to a common vertex, demanding an invariant mass in an interval of $\pm 10 \text{ MeV}/c^2$ [$\approx 3\sigma$] ($\pm 4 \text{ MeV}/c^2$ [$\approx 3\sigma$]) around the nominal K_S^0 (Λ) mass value [19] and applying the following requirements:

- the distance of closest approach between daughter particles at the decay vertex should be less than 3 cm;
- the distance between the vertex position and IP in the plane transverse to the beam direction should be greater than 0.01 cm;
- the angle α between the K_S^0 (Λ) momentum vector and the vector pointing from the IP to the K_S^0 (Λ) decay vertex, measured in the plane transverse to the beam direction, should satisfy $\cos \alpha > 0.99$;
- the vertex fit should have $\chi^2 < 100$ (10) for K_S^0 (Λ).

A sample of Λ_c^+ hyperons is reconstructed in the $\Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c^+ \rightarrow pK_S^0$, and $\Lambda_c^+ \rightarrow \Lambda\pi^+$ decay modes. We apply a mass requirement on the reconstructed Λ_c^+ candidates, demanding the invariant mass be within the $10 \text{ MeV}/c^2$ ($\approx 3\sigma$) interval around the nominal mass value [19].

4. B_s^0 -meson Reconstruction

We fit the Λ_c^+ and $\bar{\Lambda}$ momentum vectors and the π track to a common B_s^0 vertex. To reject backgrounds including displaced tracks (e.g., unreconstructed K_S^0 and Λ decays), we impose a loose requirement on the vertex-fit quality for the B_s^0 . Signal candidates are identified by two kinematic variables computed in the $\Upsilon(5S)$ rest frame: the beam-energy constrained mass $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_{B_s^0}^2}$ and the energy difference $\Delta E = E_{B_s^0} - E_{\text{beam}}$, where E_{beam} is the beam energy, and $E_{B_s^0}$ and $p_{B_s^0}$ are the energy and momentum, respectively, of the reconstructed B_s^0 candidate. For the $\Upsilon(5S) \rightarrow B_s^0 \bar{B}_s^0$ production channel, signal events correspond to a cluster at $(m_{B_s^0}, 0)$ in the M_{bc} vs. ΔE plane. For the $\Upsilon(5S) \rightarrow B_s^{*0} \bar{B}_s^0$ [$B_s^{*0} \bar{B}_s^{*0}$] channel, the photon from the $B_s^{*0} \rightarrow B_s^0 \gamma$ is not reconstructed and so signal events cluster at $((m_{B_s^0} + m_{B_s^{*0}})/2, (m_{B_s^0} - m_{B_s^{*0}})/2)$ [$(m_{B_s^{*0}}, m_{B_s^0} - m_{B_s^{*0}})$] in the M_{bc} vs. ΔE plane. We retain B_s^0 meson candidates with $M_{bc} > 5.3 \text{ GeV}/c^2$ and $|\Delta E| < 0.3 \text{ GeV}$ for further analysis.

To suppress $e^+e^- \rightarrow c\bar{c}$ background, we require that the ratio R_2 of the second and zeroth Fox-Wolfram moments [20] be less than 0.5. We also specify that the angle Θ_{thrust} between the thrust axis of the B_s^0 candidate in the $\Upsilon(5S)$ frame and the thrust axis of the rest of the event satisfies $|\cos \Theta_{\text{thrust}}| < 0.85$. The mass window of the Λ_c^+ candidate, R_2 and Θ_{thrust} requirements are optimized by maximizing a figure of merit (FOM) $N_{\text{sig}}/\sqrt{N_{\text{bkgd}}}$, where N_{sig} is the expected number of signal events from Monte Carlo simulation and N_{bkgd} is the expected number of background events estimated from the ΔE sidebands in the data.

Signal Monte Carlo samples of 120000 events each for different B_s^0 -meson production modes and Λ_c^+ decay channels are used to evaluate the response of the detector and determine its efficiency. Events are generated using the EvtGen program; the detector response is simulated with GEANT [21]. We model the $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^-$ decay according to phase space.

5. Fit Procedure and Results

We apply an unbinned extended maximum likelihood fit simultaneously to the three two-dimensional M_{bc} vs. ΔE spectra, corresponding to different Λ_c^+ subchannels. Signal and background distributions are parameterized separately for all subchannels, taking each function to be the product of shapes in M_{bc} and ΔE .

The contribution of the B_s^0 production channel C (C being $B_s^{*0} \bar{B}_s^{*0}$, $B_s^{*0} \bar{B}_s^0$ or $B_s^0 \bar{B}_s^0$) is parameterized by a two-dimensional Gaussian with parameters determined from the Monte Carlo simulation. The typical resolution in M_{bc} is 3.6 MeV/ c^2 and in ΔE is between 8.8 MeV and 9.9 MeV. The number of signal events for the channel C is written as:

$$\begin{aligned} N_C^{pK\pi} &= N_{\bar{B}_s^0} f_C \mathcal{B}_{\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^-} \mathcal{B}_{\Lambda_c^+ \rightarrow pK^- \pi^+} \mathcal{B}_{\Lambda \rightarrow p\pi^-} \epsilon_C^{pK\pi} \\ N_C^{pK_S^0} &= N_{\bar{B}_s^0} f_C \mathcal{B}_{\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^-} \mathcal{B}_{\Lambda_c^+ \rightarrow pK_S^0} \mathcal{B}_{K_S^0 \rightarrow \pi^+ \pi^-} \mathcal{B}_{\Lambda \rightarrow p\pi^-} \epsilon_C^{pK_S^0} \\ N_C^{\Lambda\pi} &= N_{\bar{B}_s^0} f_C \mathcal{B}_{\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^-} \mathcal{B}_{\Lambda_c^+ \rightarrow \Lambda \pi^+} \mathcal{B}_{\Lambda \rightarrow p\pi^-}^2 \epsilon_C^{\Lambda\pi}, \end{aligned} \quad (1)$$

where f_C is the probability for the B_s^0 -meson to be produced through the channel C and ϵ is the reconstruction efficiency that is determined from the Monte Carlo simulation. For the fractions f_C , we use the following values [17]: $f_{B_s^{*0} \bar{B}_s^{*0}} = (87.0 \pm 1.7)\%$, $f_{B_s^{*0} \bar{B}_s^0} = (7.3 \pm 1.4)\%$, and $f_{B_s^0 \bar{B}_s^0} = 1 - f_{B_s^{*0} \bar{B}_s^{*0}} - f_{B_s^{*0} \bar{B}_s^0}$. The $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^-$ branching fraction is a common parameter shared among subchannels, while the world average values [19] are used for the intermediate branching fractions. The average reconstruction efficiency is found to be 12.5% for the $pK\pi$, 5.9% for the pK_S^0 , and 8.7% for the $\Lambda\pi$ subchannel.

Background shapes are described with an ARGUS threshold function [22] in M_{bc} and a linear function in ΔE . We exclude the $\Delta E < -150$ MeV region from the fit to avoid contributions from possible $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^- \pi^0$ decays, where the π^0 is not reconstructed. This cutoff is verified by Monte Carlo simulation of $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^- \pi^0$ and $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \rho^-$ decays.

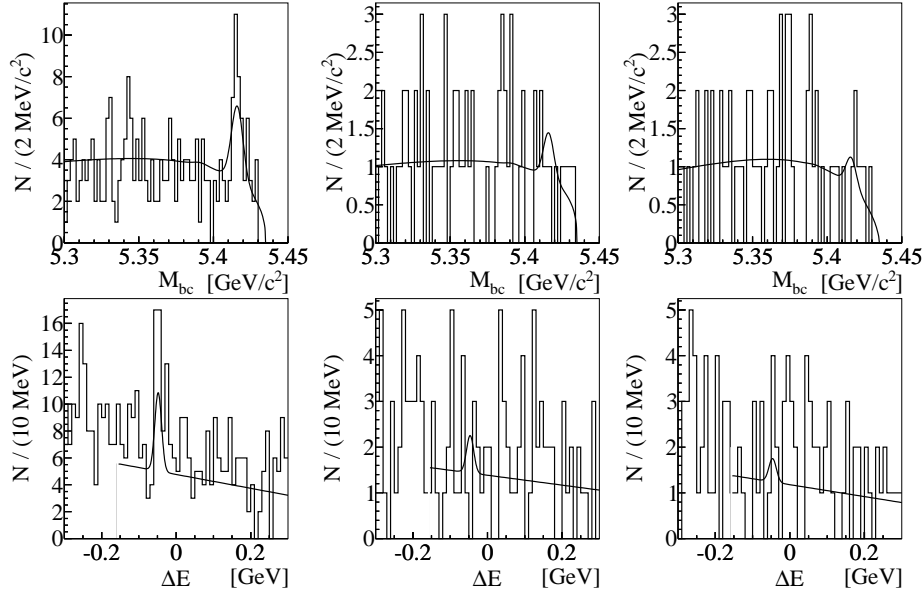


Figure 1: M_{bc} and ΔE projections for $\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-$ followed by $\Lambda_c^+ \rightarrow pK^- \pi^+$ (left column), $\Lambda_c^+ \rightarrow pK_S^0$ (center column) and $\Lambda_c^+ \rightarrow \pi\pi^+$ (right column). M_{bc} spectra (top row) are for events in the $B_s^{*0} \overline{B}_s^{*0}$ signal region ($-71 \text{ MeV} < \Delta E < -23 \text{ MeV}$) and ΔE spectra (bottom row) of the $\Lambda_c^+ \overline{\Lambda} \pi^-$ combinations are for events in the $B_s^{*0} \overline{B}_s^{*0}$ signal region ($5.405 \text{ GeV}/c^2 < M_{bc} < 5.427 \text{ GeV}/c^2$). The selection requirements and the fit are described in the text.

The fit gives a $\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-$ branching fraction of $(3.6 \pm 1.1) \times 10^{-4}$, which corresponds to signal yields of 20.3, 3.0 and 1.9 events for the $\Lambda_c^+ \rightarrow pK^- \pi^+$, $\Lambda_c^+ \rightarrow pK_S^0$ and $\Lambda_c^+ \rightarrow \pi\pi^+$ subchannels, respectively. The statistical significance of the observed signal is 4.4σ , which is calculated as $\sqrt{-2 \ln(L_0/L)}$, where L_0 and L are the likelihoods with the branching fixed at zero and at the best-fit value, respectively. This result provides the first evidence of a baryonic B_s^0 decay. Figure 1 shows the one-dimensional M_{bc} and ΔE projections for B_s^0 candidates from the $B_s^{*0} \overline{B}_s^{*0}$ signal region ($5.405 \text{ GeV}/c^2 < M_{bc} < 5.427 \text{ GeV}/c^2$, $-71 \text{ MeV} < \Delta E < -23 \text{ MeV}$).

For the systematic error calculation, we change the fixed signal parameters of the fit, reconstruction efficiencies, and fractions f_A within their uncertainties, which gives a contribution of $^{+1.1}_{-1.2}\%$, and change the boundaries of the fit, which results in a $^{+0.4}_{-0.3}\%$ uncertainty. None of these fit variations lower the signal significance within the rounding accuracy. We also include a 0.35% per track error to account for reconstruction uncertainties, a correlated systematic error of 2% per p and 1% per π or K to account for the particle identification efficiency, an uncertainty of $^{+0.0}_{-6.8}\%$ due to the difference between data and Monte Carlo for tracks displaced from the IP and errors for all variables that enter into Eqn. (1). Uncertainties from all sources are summarized in Table 1 and are summed in

Table 1: Systematic uncertainties on $\mathcal{B}(\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-)$

Source	Relative uncertainty, %
Fit parameters	+1.1 -1.2
Cutoff	+0.4 -0.3
Tracking efficiency	± 2.1
Particle identification	± 8.0
Displaced tracks	+0.0 -6.8
$\mathcal{B}_{K_S^0 \rightarrow \pi^+ \pi^-}$	± 0.1
$\mathcal{B}_{\Lambda \rightarrow p \pi^-}$	± 0.8
Total	+8.4 -12.8

quadrature.

Finally, we obtain the branching fraction:

$$\mathcal{B}(\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-) = \left(3.6 \pm 1.1[\text{stat.}] \pm_{-0.5}^{+0.3}[\text{syst.}] \pm 0.9[\Lambda_c^+] \pm 0.7[N_{\overline{B}_s^0}] \right) \times 10^{-4},$$

where the uncertainties due to the Λ_c^+ absolute branching fractions [19] and total number of B_s^0 -mesons are shown separately. The $B^- \rightarrow \Lambda_c^+ \overline{p} \pi^-$ mode, which represents a similar decay channel in the B_u -meson sector, has a branching fraction of $(2.8 \pm 0.8) \times 10^{-4}$ [19].

To study the observed shapes of the signal and background, we use only the $\Lambda_c^+ \rightarrow p K^- \pi^+$ subchannel as it contains the major portion of the signal. First, we examine distributions in the Λ_c^+ sidebands from $20 \text{ MeV}/c^2 < |M(p K^- \pi^+) - m_{\Lambda_c^+}| < 50 \text{ MeV}/c^2$ and find no peaking structures in the signal area. Monte Carlo samples of known $\Upsilon(5S)$ decays that have six times the statistics of the dataset are analysed using the same reconstruction procedure and requirements as described above. No hints for the peaking structures in the signal M_{bc} and ΔE variables are seen. Finally, we check $\Upsilon(5S) \rightarrow B^{(*)} \overline{B}^{(*)}(\pi)$ processes [19] in which the B^0 decays to $\Lambda_c^+ \overline{\Lambda} \pi^-$. About 120000 signal events are generated and then analysed using the same reconstruction procedure and requirements as described above. We find no peaking structures in the signal region, while a significant background contribution in the $\Delta E < -200 \text{ MeV}$ region is seen. From the above checks, we conclude that the signal peak stems indeed from $\overline{B}_s^0 \rightarrow \Lambda_c^+ \overline{\Lambda} \pi^-$ decays.

To investigate the possibility of a threshold enhancement, which is common in baryonic decays of $B_{u,d}$, including the related decay $B^- \rightarrow \Lambda_c^+ \overline{p} \pi^-$ [4], we extract the signal yield in baryon-antibaryon mass bins and, after total reconstruction efficiency corrections, obtain differential branching fractions as a function of $M(\Lambda_c^+ \overline{\Lambda})$; these are shown in Fig. 2(a). A fit with a phase-space Monte Carlo simulated distribution with floating normalization gives a statistical compatibility of 19%. We repeat the same procedure for other two-particle

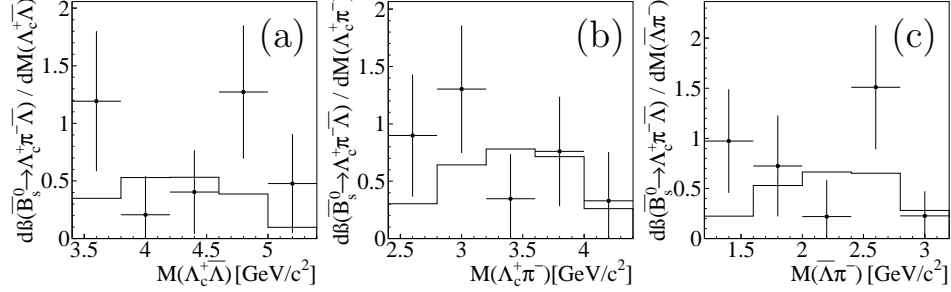


Figure 2: Differential branching fraction as a function of (a) $M(\Lambda_c^+ \bar{\Lambda})$, (b) $M(\Lambda_c^+ \pi^-)$, (c) $M(\bar{\Lambda} \pi^-)$. Points are the data; the solid histogram is the result of the phase-space fit. The vertical axis unit is $10^{-4}/(400 \text{ MeV}/c^2)$.

invariant masses: $\Lambda_c^+ \pi^-$ [see Fig. 2(b)] and $\bar{\Lambda} \pi^-$ [see Fig. 2(c)], finding 41% and 22% compatibility with the phase-space hypothesis. In general, we observe a hint of the typical near-threshold peak in the baryon-antibaryon mass spectrum, while an enhancement to the right could be explained by some decay resonant structures. However, the present statistical precision is not sufficient to investigate this effect definitively.

6. Summary

In conclusion, we report the first evidence for the $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^-$ decay and measure its branching fraction to be $(3.6 \pm 1.1[\text{stat.}]_{-0.5}^{+0.3}[\text{syst.}] \pm 0.9[\Lambda_c^+] \pm 0.7[N_{\bar{B}_s^0}]) \times 10^{-4}$ with a 4.4σ significance, including systematics. The observed $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda} \pi^-$ process represents the first instance of a B_s baryonic decay.

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